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Non-Central Heavy-Ion Collisions are the Place to Look for DCC

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We give two reasons why we believe that non-central ultrarelativistic heavy ion collisions are the place to look for the disoriented chiral condensates (DCC). First, we argue that the most probable quench scenario for the formation of DCC requires non-central collisions. Second, we show by numerical simulations that strong electromagnetic fields of heavy ions can exert a surprisingly large effect on the DCC domain formation through the chiral anomaly. The effect again requires non-central collisions. Interestingly, the result of simulations is consistent with the formation of correlated two domains of the chiral condensate, which are aligned in space, perpendicular to the scattering plane, but misaligned in isospin space.

1. INTRODUCTION

Recently, the possibility of the formation of chirally misaligned domains in very high energy collisions of hadrons or heavy nuclei has attracted a lot of interest. These domains are called disoriented chiral condensates. A DCC domain is a coherent excitation of the pion fields and corresponds to a local and coherent rotation of the chiral order parameter of the QCD vacuum. There have been considerable activities in both experimental and theoretical research on DCC.

So far, analyses of high energy heavy ion collisions has focused on central collisions [1]. It is because these collisions are thought to be the most effective ones in establishing the conditions required for the chiral phase transition in hadronic matter at high temperature or baryon density. Here we discuss the possible importance of non-central collisions of ultrarelativistic heavy ions for the formation of DCC domains. The reasons are twofold, as we discuss in the following.

2. QUENCH

Although the possibility of DCC has been pointed out on general grounds [2,3,4], the only mechanism known to date for the formation of DCC domains is the quench mechanism proposed by Rajagopal and Wilczek [5]. Its essence is summarized by the important condition: At some initial moment, the matter must be out of equilibrium. A way of creating out-of-equilibrium field configurations in isospin space is to proceed through the following two-step process. 1) First, create a thermally equilibrated and chirally symmetric phase of matter. 2) Then, let it cool down rapidly so that the configuration of the

chiral fields remains around the symmetric point, while the effective potential favors a state with spontaneously broken chiral symmetry.

Central collisions are where the initial conditions are expected to correspond to the highest energy density. However, at the same time they are where the characteristic time scales are largest, because the heated volume is of maximal size. For the purpose of creating field configurations which are out of equilibrium in isospin space, a smaller time scale for the expansion of the system is better. In this sense, central collisions are where the formation of DCC may be less likely. On the other hand, it is less probable that chiral symmetry is restored in very peripheral collisions at all. Thus, we conclude that it is quite important to investigate not fully central but also non-peripheral events in the DCC hunt.

3. ANOMALY

Ultrarelativistic heavy ions are sources of strong electric and magnetic fields. When two high energy heavy nuclei collide and the chirally restored phase is created, strong electric and magnetic fields coexist. It was pointed out in Ref. [6] that the electric and magnetic fields affect the motion of the chiral field through the Adler-Bell-Jackiw anomaly. In the following argument, we use the linear sigma model whose parameters are the same as those used in Ref. [7]. The anomaly gives the following additional term to the effective potential,

$$V_{\text{anomaly}} = -\frac{\alpha}{\pi f_\pi} \vec{E} \cdot \vec{H} \pi_3, \quad (1)$$

where α and f_π are the electromagnetic fine structure constant and pion decay constant, respectively. By using the point charge approximation, one can express $\vec{E} \cdot \vec{H}$ as

$$\vec{E} \cdot \vec{H} = -\frac{2Z^2 e^2}{M} \frac{\gamma^2}{R_1^3 R_2^3} (\vec{r} \cdot \vec{L}), \quad (2)$$

where Z and M are the charge and mass of each colliding nucleus (we are assuming that identical nuclei are colliding like at RHIC), respectively, and $\vec{L} = \vec{b} \times M \vec{v}$ with impact parameter \vec{b} , and

$$R_{1,2} = \sqrt{\gamma^2(z \mp vt)^2 + \left(\vec{r}_\perp \pm \frac{\vec{b}}{2}\right)^2}. \quad (3)$$

We have taken the collision point as the origin of the coordinate system and the z axis as the collision axis in the above expression. It indicates that the anomaly effect vanishes in very central collisions. In non-central collisions, the anomaly effect vanishes on the scattering plane, and $\vec{E} \cdot \vec{H}$ has definite signs in the upper and lower half-spaces, and they are opposite with each other.

Since the anomaly effect is proportional to α^2 and the duration of heavy ion collisions is short at high energies, the change of the average value of the π_3 field during a collision is almost negligible and only $\dot{\pi}_3$, the conjugate field of π_3 , is changed. Thus, the effect of the anomaly is summarized as a quasi-instantaneous kick to the $\dot{\pi}_3$ field which is coherent within the upper and lower half-spaces and takes opposite signs in each half-space [6].

4. SIMULATION

To uncover the effect of the anomaly induced kick on the formation of DCC, we have run dynamical simulations of the linear sigma model. The code is essentially the same as developed in Ref. [7]. The details will be reported elsewhere [8]. We have implemented the effect of the kick in the initial condition on the conjugate field $\dot{\pi}_3$, providing a uniform shift that is opposite in sign in the upper and lower half-spaces with regard to the scattering plane,

$$\langle \Delta\dot{\pi}_3 \rangle = \text{sgn}(y)a_n m_\pi^2, \quad (4)$$

where a_n is a parameter and we have defined the y axis to be perpendicular to the scattering plane. In the following calculation, we shall take 0.1 for a_n in order to simulate the situation expected to be realized at RHIC and take the quench initial condition defined in Ref. [7]. In order to concentrate on the effect of the anomaly kick to the time evolution of the system, we assume in this paper that the size of the system is infinite in the transverse directions, while we assume longitudinal boost invariance [9] in the longitudinal direction.

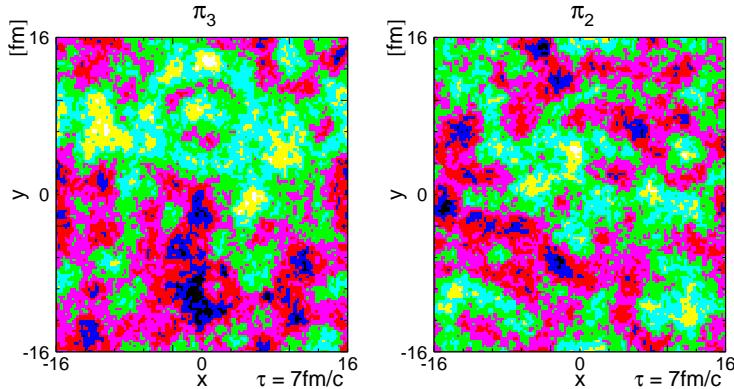


Figure 1. Distribution of the π_3 field strength at $\tau = 7$ fm.

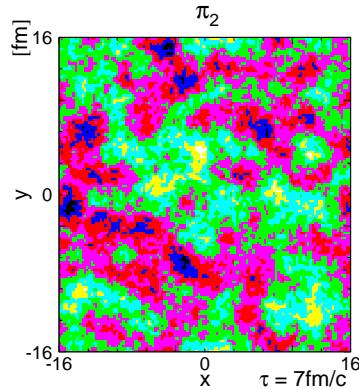


Figure 2. Distribution of the π_2 field strength at $\tau = 7$ fm.

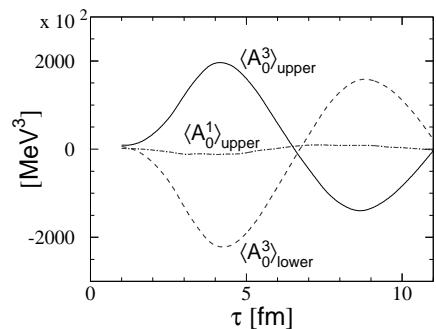


Figure 3. Behavior of A_0^1 and A_0^3 averaged over the upper and lower half-spaces and over 10 events.

Compared to the typical fluctuation of $\dot{\pi}_3$, the effect of the anomaly kick given by Eq. (4) with $a_n = 0.1$ appears to be completely negligible. Our numerical simulations, however, show that a coherent kick of such a small amplitude has a surprisingly large effect on the time evolution of the π_3 field. In Figs. 1 and 2, we show the distribution of the π_3 field, whose conjugate is kicked by the anomaly, and π_2 field, whose conjugate is not kicked, respectively, at $\tau = 7$ fm in an event. The initial proper time τ_0 has been taken to be 1 fm. We can clearly see the asymmetry in the time evolution of the π_3 field between the upper and lower half-spaces, while no such asymmetry is observed in the π_2 field. This tells us that a kick of small magnitude induces a coherent motion of the π_3 field.

However, the pion field strengths themselves are not observables. It is the currents, the vector V_μ^i and axial vector current A_μ^i , that couple to physical observables, where μ and

i are Lorentz and isospin indices, respectively, and V_μ^i and A_μ^i are defined as

$$\begin{aligned} V_\mu^i &= \varepsilon^{ijk} \pi^j \partial_\mu \pi^k, \\ A_\mu^i &= \pi^i \partial_\mu \sigma - \sigma \partial_\mu \pi^i. \end{aligned} \quad (5)$$

We show in Fig. 3 the behavior of A_0^1 and A_0^3 averaged over the upper and lower half-spaces and over 10 events. This vividly shows that striking coherence in A_0^3 throughout each of the upper and lower half-spaces so that each can be considered as a DCC domain defined by the distribution of A_0^3 . On the other hand, A_0^1 does not show coherent behavior. Neither does V_0^1 nor V_0^3 . We have confirmed that this is not affected by the finiteness of the system by carrying out simulations with finite transverse dimensions.

5. SUMMARY

We have pointed out, on the basis of two reasons, the importance of semi-central high energy heavy ion collisions in the search for DCC. First of all, it is required by the quench scenario. Secondly, it is preferred by the chiral anomaly in heavy ion collisions. $\vec{E} \cdot \vec{H}$ takes opposite signs in each side of the scattering plane and couples with the neutral pion field π_3 through the chiral $U(1)$ anomaly. Its effect can be summarized as a quasi-instantaneous kick to $\dot{\pi}_3$. Its strength appears negligibly small, but our numerical simulations have indicated that the time evolution of the chiral order parameter is such that the anomaly-induced coherence in π_3 component is little affected by other field components in spite of their strong coupling at the Lagrangian level. π_3 and A_0^3 show definite asymmetry between the upper and lower half-spaces, and are highly coherent within each half-space.

Thus, the anomaly induces the formation of DCC domains, which are aligned in space, i.e., one in the upper half-space and one in the lower half-space, but misaligned in isospin space. Because of its definite sign, the spatial asymmetry could serve as an additional experimental signal for the formation of DCC in heavy ion collisions, in the context of an event-by-event analysis with scattering plane identification, which is now experimentally feasible.

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